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Ferroresonant Circuits

By the Engineering Department, Aerovox Corporation

If a saturable reactor is made the inductive element of a tuned circuit, either series-resonant or parallel-resonant, varying the current through the reactor will vary the resonant frequency of the combination. This is the simple basis of all *ferroresonant* circuits. The most efficient manifestation of this effect occurs when a large resonant frequency shift is obtained as the result of a small change in control current, usually through a separate winding. The ferroresonant effect may be utilized in various ways in electronic and electrical equipment.

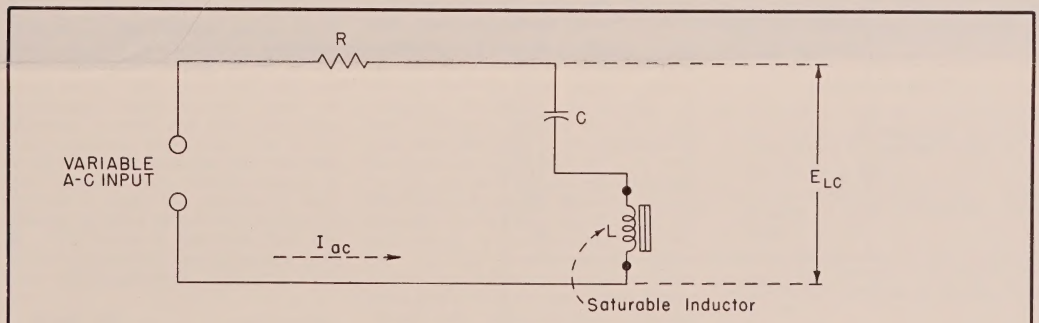
Ferroresonant circuits recently have been designed to perform as amplifiers, triggers, switches, flip-flops, gates and oscillators. Ferroresonant elements find application in electronic counters, computers and other digital devices, frequency dividers, signal amplifiers, and automatic control circuits. Closely related to the magnetic amplifier, the ferroresonant circuit is tubeless and has unlimited life. Ferroresonant elements are rugged and can be made extremely small in size. Unlike the magnetic amplifier, ferroresonant devices may be operated at high supply-voltage frequencies, enabling high-speed switching performance and high-frequency amplification.

Basic Ferroresonant Circuit

In Figure 1, a coil having a saturable core is connected in series with a conventional capacitor, resistor, and continuously variable a-c source. This is the basic ferroresonant circuit. The zero-current inductance of coil L and the capacitance C are chosen such that the series-resonant frequency, f_r, of the combination is somewhat lower than the supply-voltage frequency.

Figure 2 shows the response of this simple circuit. As the supply voltage is increased, the current (I_{ac}) through the coil, capacitor, and resistor increases, as shown in Figure 2(B), and the voltage (E_{LC}) across the inductance-capacitance leg increases from zero to a maximum at point A. As the current is increased beyond this level, voltage E_{LC} would continue to increase except that the core of the coil begins to saturate and this lowers the inductance. Accordingly, the voltage begins to fall after point A.

The decreasing inductance of the coil causes the circuit to approach



BASIC FERRORESONANT CIRCUIT

FIGURE 1.

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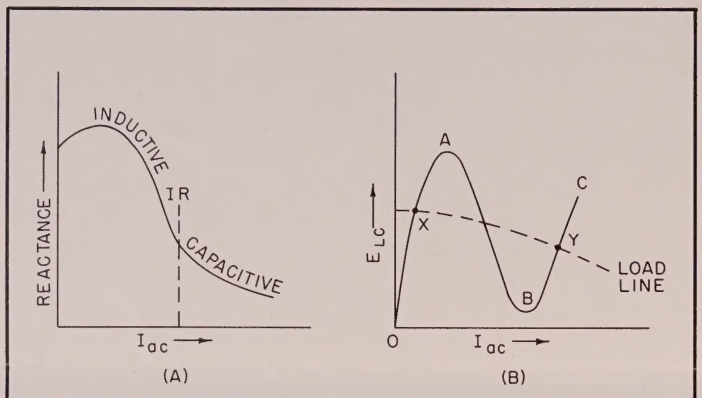


RESPONSE CURVES OF FERRORESONANT CIRCUIT

FIGURE 2.

resonance, the impedance of the LC arm decreasing. The voltage drop E_{LC} accordingly decreases, dropping to point B at resonance. Although $X_L = X_C$ at this point, B does not dip completely to the zero-voltage line because of resistive losses, chiefly in the coil.

As the current is increased beyond this point, further saturation of the core and consequent lowering of the inductance tunes the circuit beyond resonance, and voltage E_{LC} again rises, as from B to C. Figure 2(A) shows the variation of circuit reactance with current. At resonance, the voltage drop, IR, is due only to resistive losses mainly in the coil copper. Before this point, the circuit reactance is inductive, and after this point is capacitive.

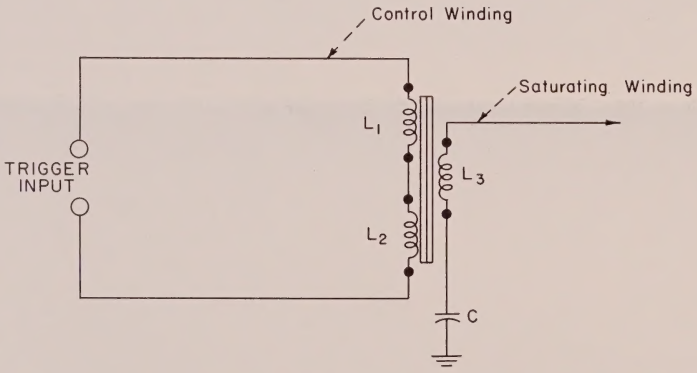
The plot of Figure 2(B) is seen to have the S-curve shape which is typical of the characteristics of certain bistable and oscillating systems. Thus, the response is characterized by two stable regions of "positive impedance" (OA and BC) connected by an unstable region of "negative impedance" (AB).

This circuit can exhibit true bistability. That is, its current may have either a high or a low discrete value at a particular voltage, and this current value can be maintained indefinitely unless the operator switches it to its second value. Thus, referring to Figure 2(B), the current might have a low value X or a high value Y along the inscribed nonlinear load line. The current will not hold along the unstable negative slope, AB, but can be made to shift from some point along OA to a point along BC, quickly traversing AB and locking along BC. If the ferroresonant element is operated in a suitable circuit, conduction may be triggered back and forth between the two stable states. This action suits the ferroresonant element ideally as a binary device.

Ferroresonant Flip-Flops

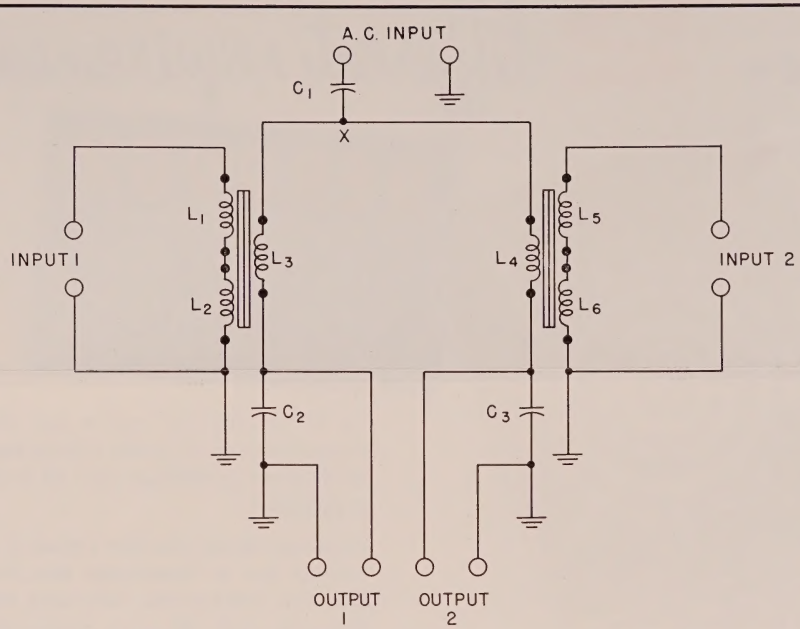
One of the most promising and already exploited applications of small ferroresonant elements is as flip-flops in digital computers, counters, and frequency dividers.

A second, coupled winding might be added to the simple circuit of Figure 1. This modification is shown in Figure 3. Here, the *control* winding actually consists of two coils (L_1 and L_2) which are connected series-bucking to isolate the TRIGGER INPUT terminals from the a-c supply. A d-c trigger pulse of either polarity applied to the control winding then would reduce momentarily



CONTROLLED FERRORESONANT ELEMENT

FIGURE 3.



FERRORESONANT FLIP-FLOP

FIGURE 4.

the inductance of L_3 and allow the current to jump from X (Figure 2B) to Y. The current then would latch at the second value and would be unaffected by further pulses applied to the control winding, since the high current at point X would be sufficient to maintain the core saturated.

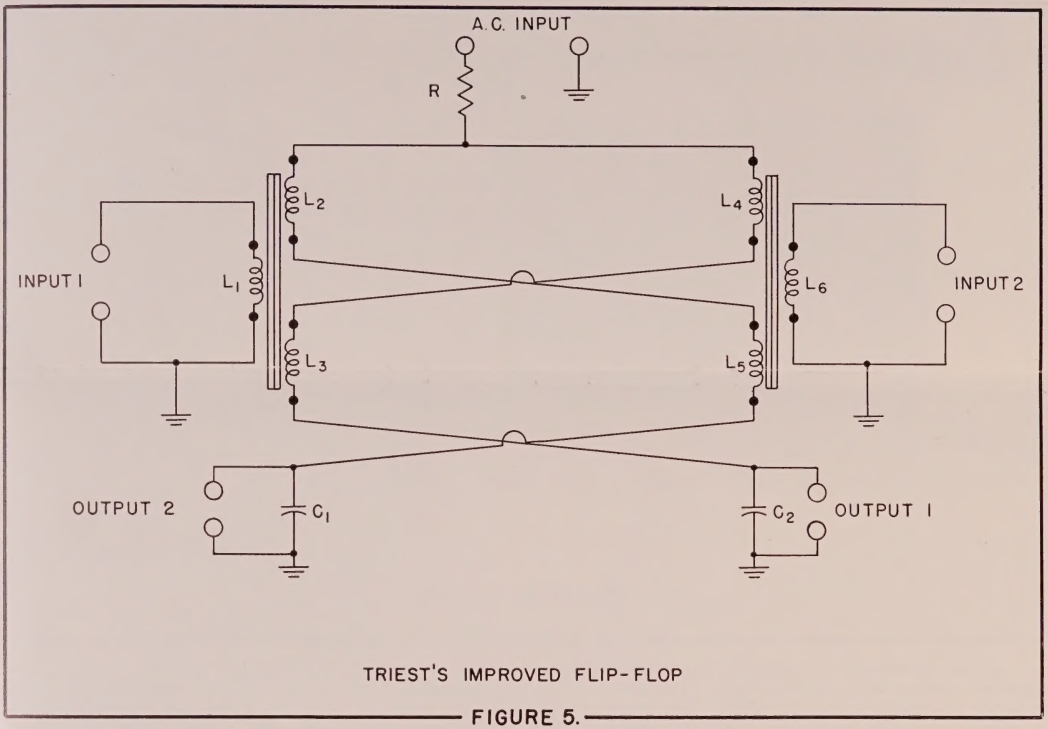
The fact that the current in this simple circuit cannot be returned to its initial level by alternate pulses but only by a momentary interruption of the a-c supply line prevents use of the circuit directly as a flip-flop even though it is bistable.

Figure 4 is an arrangement of two ferroresonant elements in parallel. Each has a separate control coil. This arrangement provides good flip-flop action. The circuit is due to Isborn.[2] Here, L_3C_2 and L_4C_3 correspond to the simple elements shown previously in Figure 1. Capacitor C_1 provides a series reactance which is common to both ferroresonant legs. The control winding for the left leg consists of coils L_1 and L_2 connected in series-bucking to prevent transmission of the a-c supply energy back to the INPUT 1 terminals. Similarly, the control winding of the right leg consists of L_5 and L_6 connected in series-bucking to prevent a-c coupling back to the INPUT 2 terminals.

With the proper magnitude of reactance at C_1, only one ferroresonant leg can conduct in the high-current state at one time. If both legs should attempt to operate at this level simultaneously at high current, the increased voltage drop at point X would reduce the leg drops ($E_{L_3C_2}$ and $E_{L_4C_3}$) below the resonant value and neither one could latch-in at high current. When both legs drop to low-current conduction (or attempt to do so), the drop across C_1 falls and the voltage at point X rises to such a high value that either the left or right leg will "fire."

In order to examine operation of this circuit, assume that the left leg (L_3C_2) is conducting high and that the right leg (L_4C_3) is conducting low. Output 1 will be high (TRUE or 1 in binary notation) and output 2 will be low (binary FALSE or 0). A pulse applied to INPUT 1 will have no effect, since the core already is saturated in this leg of the circuit. Coil L_4, however, is carrying low current and its core is not saturated. A pulse applied to INPUT 2 therefore will lower the inductance of L_4, saturating the core of this coil and moving the L_4C_3 leg into resonance. The high current then will reduce the voltage at point X momentarily to such an extent that L_3C_2 is detuned from resonance and drops to the low current condition. High conduction then shifts to the right leg, and OUTPUT 2 becomes high. Thus, the two outputs always are of opposite phase and change states with respect to each other.

For single-input operation, INPUT 1 and INPUT 2 may be connected together and the triggering pulse thus applied simultaneously to L_1L_2 and L_5L_6. Successive pulses then will cause high conduction to flip back and forth between the two legs, and a given pair of OUTPUT terminals will have high output during only half of the number of input pulses. The circuit thus acts as a frequency halver.



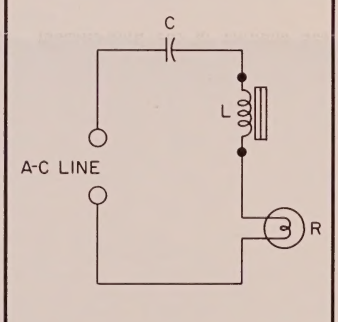
TRIEST'S IMPROVED FLIP-FLOP

FIGURE 5.

Appreciable power gain is obtained. Rutishauser[4] has pointed out that by providing control coils of many turns, the required triggering current can be made very small. One flip-flop thus can drive others without intermediate driver stages. In this way, it is comparatively simple to set up tubeless binary counters, ring counters, and similar circuits. Rutishauser has had a ring of 32 stages operating satisfactorily and states that about 50 stages would appear to be the upper limit.

Aside from being tubeless, simple, and capable of extreme miniaturization, ferroresonant flip-flops with small cores of thin material may be operated at high power-supply frequencies (1 Mc and higher) allowing rapid switching. Isborn mentions that the entire switching operation takes place in a period equal to approximately 5 cycles of the supply frequency.[2] Another considerable advantage of the ferroresonant flip-flop is its low power requirement. This results from the use of reactive components in the circuit. Furthermore, although high current is shifting from one leg to the other, the load on the power supply is constant. Another advantage is the low heat radiation which results from low power dissipation and the absence of tube filaments.

Triest of International Business Machines Corp. has patented an improved ferroresonant flip-flop[6], shown in basic arrangement in Figure 5.



MACKAY'S FERRORESONANT RELAXATION OSCILLATOR

FIGURE 6.

This circuit employs a pair of saturating windings (L_2L_3 and L_4L_5) on each core and cross-couples them.

A low, lagging current flows in the less saturated leg and a high, leading current in the more saturated leg. The patent claims that the cross coupling increases the difference between the two current magnitudes, creating in fact a wide gap. The common resistance, R, in Figure 5 serves the same purpose as the common capacitance, C_1, in Figure 4.

The main saturable inductor windings are L_2 and L_4. Coils L_3 and L_5 are the auxiliary windings. When the left leg is resonant, high leading current in L_5 produces flux in the core of the right leg to induce an e. m. f. in L_4. This voltage opposes the lagging current in L_4. The net result of this action is a reduction of the current in the right leg and an increase in the current in the left leg. It is in this way that the gap between the values of voltage drop across capacitors C_1 and C_2 is widened. Outputs are taken from across these two capacitors.

Additional Applications

Mackay has developed several interesting circuits of a highly practi-

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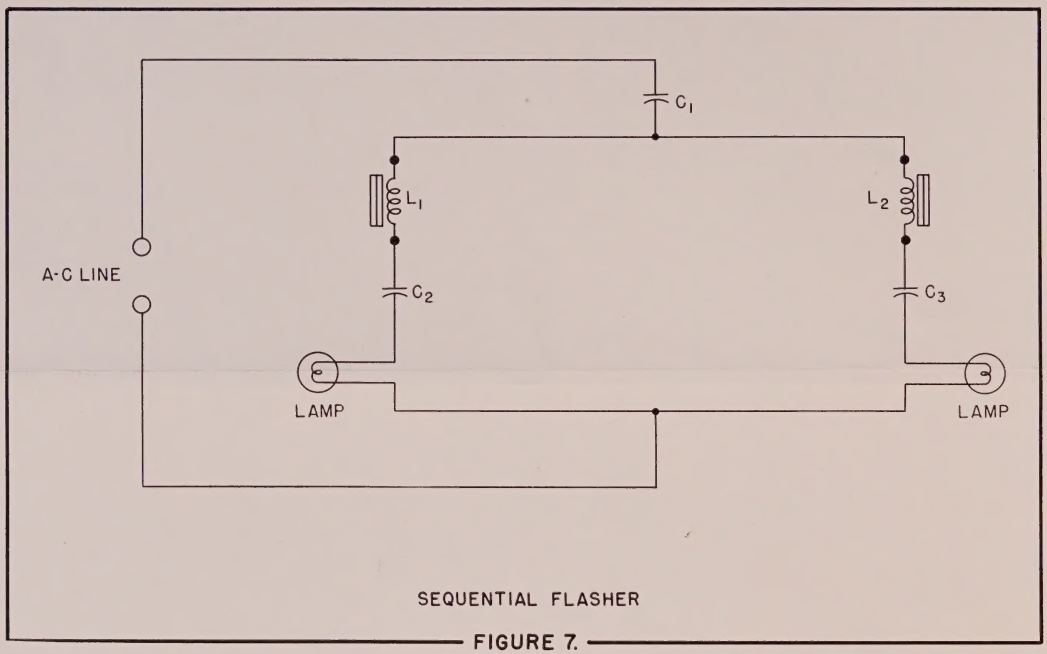

FIGURE 7.

cal nature in which ferroresonant elements are combined with the nonlinearity of tungsten lamp filaments to obtain relaxation oscillations and the intermittent operation of lamps.[3] This scheme has been described also in the popular literature.[5]

Figures 6 and 7 show two of Mackay's circuits. In Figure 6, L is the primary winding of a small filament transformer (Stancor P-6135) and serves well enough as a saturable reactor at the current levels involved. C is a 12-microfarad capacitor (non-electrolytic) and R is a 100-watt lamp. The latter exhibits low resistance (high current) when its filament is cold, and high resistance (low current) when hot. The L and C combination behaves like the simple ferroresonant circuit shown in Figure 1 when the current is high enough to start saturation of the coil, L. The circuit is operated from the 115-volt ac power line through a variable autotransformer such as a Variac.

When the circuit is switched-on, the filament is cold and its resistance low. The lamp accordingly lights from the correspondingly high current flow and the ferroresonant circuit operates at its high-current point. As the filament heats, its resistance increases, the current accordingly drops and will snap (flip-flop fashion) to the low-current point on the ferroresonant response curve. The lamp therefore extinguishes. As the filament then cools, its resistance decreases, current again rises and soon snaps back to the high-level point to repeat the cycle of operations. When the input voltage is adjusted to a certain critical point, the lamp flashes on and off at a regular rate as the result of this ferroresonant action. Mackay gives a 5½-second ON rate with the circuit constants shown here.

The circuit shown in Figure 7 will be seen to resemble the ferroresonant flip-flop of Figure 4, minus control (trigger) windings. It consists of two "blinker" circuits of the type just described, with the addition of the common capacitor, C_1. In this circuit, L_1 and L_2 are the primary windings of small filament transformers, as before, and C_1 is a 16-microfarad non-electrolytic capacitor. C_2 and C_3 each are 12 microfarads, also non-electrolytic. Each lamp is of 100-watt size. Both lamps cannot light simultaneously because the large voltage drop across C_1, due to the resulting high current flow, would reduce the voltage across each leg of the circuit to a value much lower than the ferroresonant value and insufficient to light the lamps. However, one leg always will have enough voltage for the lamp in that leg to glow. When that lamp extinguishes, the one in the other leg ignites. Mackay has operated a number of legs through the common capacitor and observed that the lamps flash cyclically.

An obvious application of this low-frequency type of ferroresonant circuit would be as a high-intensity blinker in such applications as traffic signal beacons, railroad signals, etc. where all moving parts, relay contacts, and the like would be eliminated and continuous, unattended operation secured.

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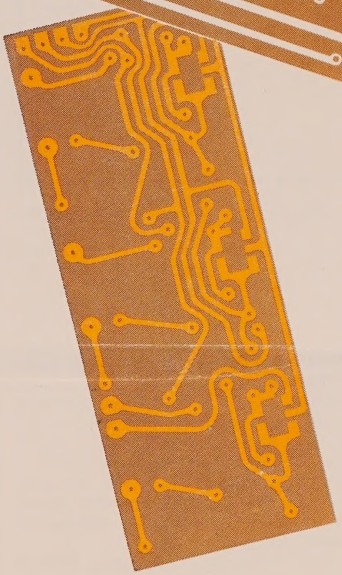

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